Journal of Strength and Conditioning Research Publish Ahead of Print
DOI: 10.1519/JSC.0000000000001201

The validity and reliability of a portable isometric mid-thigh clean pull

Conducted at School of Human Movement and Nutrition Sciences, University of Queensland, Australia

By

Lachlan P. James [1]

Llion A. Roberts[1]

G. Gregory Haff [2]

Vincent G. Kelly [1, 3]

Emma M. Beckman [1]

[1]School of Human Movement and Nutrition Sciences, University of Queensland, Australia

[2] Centre for Sport and Exercise Science Research, Edith Cowan University, Perth, Australia

[3]Brisbane Broncos Rugby League Football Club, Queensland, Australia

Corresponding Author:

Mr. Lachlan P. James, Room 212, Building 26B, School of Human Movement and Nutrition Sciences, The University of Queensland, St. Lucia, QLD 4072, Australia

Email: l.james1@uq.edu.au Phone: (+1) 604 726 7782, Fax: (+61) 7 3365 6877

ACCEPTED

Copyright © Lippincott Williams & Wilkins. All rights reserved.

ABSTRACT

This study investigated the test-retest reliability and criterion validity of force-time curve variables collected via a portable isometric mid-thigh clean pull (IMTP) device equipped with a single-axial load cell. Fifteen males with ≥ 6 months of resistance training experience attended two testing sessions. In each session, participants performed an IMTP in two separate conditions in a randomized, counterbalanced manner. The criterion condition consisted of a closed-chain IMTP configured with a force plate (IMTPf), while the experimental test was undertaken using a portable IMTP with data acquired via a single-axial load cell (IMTPl). A very high reliability (CV = 3.10, 90% CI: 2.4 - 4.6%; ICC = 0.96, 90% CI: 0.90 - 0.98) and acceptable validity (CV = 9.2, 90% CI: 7 - 14%; ICC = 0.88, 90% CI: 0.71-0.95) were found in the experimental condition for the measure of peak force. However, significant differences were present between the IMTPf and IMTPl (p<0.0001). Alternate force-time curve variables did not reach acceptable levels of validity or reliability in the experimental condition. The IMTPl is a valid and highly reliable method for assessing peak force. This provides evidence supporting the use of an IMTPl as a cost effective and portable alternative for those who wish to assess maximal force production in a similar fashion to a traditional IMTP. However, practitioners should be aware that these are slightly different tests.

Key words: Peak force, rate of force development, field-testing, strength, force-time curve

ACCEPTED

Copyright © Lippincott Williams & Wilkins. All rights reserved.

INTRODUCTION

The ability for the neuromuscular system to apply force (strength) is considered as the primary training factor for many sports (28). This quality is understood to influence a spectrum of physiological attributes critical to athletic performance such as neuromuscular power (5), injury prevention (23) and endurance performance (26). Accordingly, maximal strength is an essential component in performance profiles of athletes from a variety of sports (28). The effective assessment of the force production capabilities of skeletal muscle forms the cornerstone of many training plans, in addition to providing valuable information for research and clinical settings. The isometric mid-thigh clean pull (IMTPf) is a common method used for the quantification of maximal strength in athletic populations (8, 10, 11, 30). This test is conducted in a closed chain environment with the athlete assuming an upright position with a small amount of hip and knee flexion. Such a position is intended to replicate the beginning of the second pull phase of the clean (11).

The IMTPf provides force-time information through the collection of vertical ground reaction force (GRF) data, which allows for the calculation of variables such as peak isometric force (PF), the rate of force development (RFD), and time specific force values. The PF measure from this test shows high to practically perfect correlations to dynamic performance variables in common athletic actions such as jumping (8, 11, 19, 25), throwing (30), change of direction patterns (31) and weightlifting (8, 11, 19, 30), in addition to effectively detecting training induced changes in force (29). Likewise, RFD measures have also been related to variables in similar dynamic actions (8, 11, 19, 25). As such, the quantification of PF and RFD with the use of the IMTPf has become increasingly important to sports scientists and strength and conditioning coaches who want to evaluate the neuromuscular characteristics of their athletes. However, the instrumentation required for

ACCEPTED

Copyright © Lippincott Williams & Wilkins. All rights reserved.

such a test is expensive and thus poses a considerable limitation for its use in many applied settings. In particular, the force plate utilized to acquire GRF data can be cost prohibitive and may lack portability, which limits the performance of the test to laboratory settings. However, it might be possible to employ more affordable equipment to obtain force-time information. Specifically, a single axial load cell and accompanying software provides a possible alternative if the goal is to collect force-time data in only one axis, and likely presents a more accessible option for many in the field due to its small size and cost effectiveness. Using commonly available materials, this could be easily configured by the coach to replicate the laboratory based IMTPf.

For an assessment method to be suitable for use it must first display adequate levels of reliability. In particular, to effectively monitor the internal response to training interventions an acceptable absolute reliability as measured by the coefficient of variation (CV) is required (14, 21). For descriptive variables whereby comparisons within or between groups are necessary, an intraclass correlation co-efficient (ICC) that reaches satisfactory levels must be established to ensure relative reliability (1, 14). In addition, these calculations can determine the extent to which the experimental method simulates the criterion performance, thus establishing the criterion validity (6).

The purpose of this present experiment was to establish the test-retest reliability and criterion validity of a custom built portable isometric mid-thigh clean pull utilizing a single-axial load cell (IMTPl) in comparison to a laboratory based version of the test employing a force plate (IMTPf) for the assessment of PF. It was hypothesised that the experimental condition would reach acceptable levels of relative and absolute reliability, thereby proving a suitable alternative to the IMTPf for this measure. A secondary objective of this experiment

ACCEPTED

Copyright © Lippincott Williams & Wilkins. All rights reserved.

was to determine whether RFD and time-point specific force measures attained an acceptable degree of reliability and validity for the IMTPl.

METHODS

Experimental approach to the problem

Testing sessions were conducted at two time points separated by a minimum of 48 hours and no longer than 7 days apart (mean=3.64 ± 1.95 d). During this period, participants were instructed to refrain from exercise and alcohol for 48 hours before each session. All subjects retained the same dietary regime for each testing session. Likewise, nutritional supplementation, habitual caffeine intake and hydration was monitored to ensure they were consistent across both testing sessions. Time of day was also held constant ±2h. Testing sessions required the subjects to undertake the criterion and experimental conditions in a randomized counterbalanced manner.

Subjects

Fifteen recreationally active males (23.7±3 y; 78.4±10.27 kg; 1.78± 0.06m), with ≥ 6 months of structured resistance training experience, volunteered to participate in this study. All subjects were made aware of the risks associated with participation in this investigation and provided written informed consent. This experiment was approved by the University's Human Research Ethics Committee.

Procedures

Sessions began with a warm-up involving a series of general dynamic stretches, followed by 3 sets of 5 repetitions of dynamic mid-thigh clean pulls from the hang position,

ACCEPTED

Copyright © Lippincott Williams & Wilkins. All rights reserved.

across 30-50% of the subject's estimated 1 repetition maximum power clean. A familiarization protocol involving 3 submaximal attempts at progressively increasing intensities on the IMTPf and IMTPl was included during each testing session.

The IMTPf test required participants to position themselves on a force plate with feet at approximately hip width apart, which was then standardized for all tests performed. The bar height was adjusted to correspond to the subjects' second pull position of the power clean, resulting in hip and knee angles of 139.2±4.1° and 141.9±4.3° respectively. Participants grasped the bar with a double overhand grip, and the distance from the bar to the force plate was measured by the assessor in order to ensure positions were replicated in each testing session. The force plate was offset to the weight of the participant prior to each attempt, therefore only forces above that of the performer's body mass was used for analysis (11).

In the experimental condition, the bar height was set to replicate that of the criterion method. Participants were positioned on the base plate at the aforementioned feet spacing, with the load-cell located at mid-foot, and gripped the bar of the apparatus (described in detail in the section below) in the same manner as the IMTPf. Hip and knee angles were then assessed to ensure the position reproduced the criterion method. Following this, the strap was adjusted to ensure no vertical movement was present. The performer was then allowed 1 minute passive recovery before the aforementioned familiarization protocol.

Participants were instructed in both tests to apply a small amount of pretension then to pull on the bar "as hard and as fast as possible" for 5s (8) with strong verbal encouragement for each maximal effort across both testing sessions. Two maximal trials separated by a

ACCEPTED

Copyright © Lippincott Williams & Wilkins. All rights reserved.

minimum of 3 minutes passive recovery were performed. If the assessor did not believe it to be the participant's maximal effort, or if there was a difference of greater than 200N between trails, an additional attempt was performed (22). The trial displaying the greatest PF was used for data analysis. Following a minimum of 3 minutes passive recovery, this process was repeated for the alternate condition. This testing and data collection protocol was applied again in the second session, however with a reverse order of testing conditions.

Instrumentation

The IMTPf was configured utilizing a traditional squat rack, with an Olympic barbell (28mm in diameter) attached to safety supports via two heavy-duty ratchet straps (width: 25mm; lashing capacity: 6376N) (Figure 1). Insertions were used allowing the bar to be adjusted to the desired height at increments of 8mm. All joint angles were measured with a handheld goniometer. Placed on the ground under the secured bar was a Kistler force plate (Kistler, Ostfildern, Germany) sampling at 1000Hz from the vertical axis via native software (Kistler Bioware 5.1.3, Ostfildern, Germany). The experimental IMTPl apparatus consisted of a custom designed metal plate, 69 × 44cm in size, upon which the participant stood. A 12mm hole was made 2.2cm above centre through which an S-type load-cell (Scale Components, Australia) rated to 3865N was attached. On the underside of the baseplate a box channel elevation was secured with aluminium rivets. This allowed the plate itself to sit 20mm off the ground. Figure 2 displays the important features of the design. One end of a heavy-duty ratchet strap (width: 25mm; lashing capacity: 6376N) was secured to the load cell, while the other was attached to a traditional lat-pulldown attachment made of solid steel, 25mm in width with knurled grips and a revolving swivel hanger (Figure 1). The downward force of the bar due to gravity was measured as 60N and added to the peak force measure

ACCEPTED

Copyright © Lippincott Williams & Wilkins. All rights reserved.

used for analysis. The length of the strap was adjusted to attain the required hip and knee angles. This resulted in an immovable bar in the vertical direction only. The load-cell allowed for data sampling at 100 Hz in this axis and calibrated using native MuscleLab software (MuscleLab V8.26, Ergotest Technology, Norway).

Place Figure 1 about here

Place Figure 2 about here

Force-time curve analysis

Data reduction and extraction was conducted with a custom designed Matlab script (The Mathworks, Inc., Natick, MA). IMTPl data frequency was maintained, whilst IMTPf data was down-sampled to 100 Hz and used for comparison to the load-cell force-time data. All data were subjected to filtering via a 10 Hz Butterworth fourth-order digital low pass filter. Force-time curve analysis was undertaken in accordance with the protocols established by Haff et al.(10). The initiation of the pull was identified as the time corresponding to a force of < 20 N above rest (referred to as time 0). Subsequently, RFD was calculated from 0-30, 0-50 0-100, 0-150, and 0-250 ms. Force at given time points were also measured at 30, 50, 100, 150, 200 and 250 ms. Peak RFD (pRFD) was calculated as the highest RFD during any 20ms sampling window throughout the 5 s effort. The greatest force value at any point during the trial was identified as PF.

Statistical Analysis

Reliability and validity was calculated for each variable by way of ICC, CV, and their 90% confidence intervals (CI). The ICC and CV were also utilized for comparing IMTPf native 1000 Hz data with the down-sampled 100 Hz data. Acceptability cut offs for the ICC was set at ≥ 0.8, while ≥ 0.9 was considered high. Acceptable, and high thresholds for the CV were set at ≤ 10%, and ≤ 5% respectively. For each condition, validity measures were

ACCEPTED

Copyright © Lippincott Williams & Wilkins. All rights reserved.

performed on the mean result of testing sessions 1 and 2. Pearson product moment correlations (*r*) were employed to determine the strength of the association between conditions. All data were normally distributed, therefore repeated measures general linear models were used to identify any differences in mean performance variables during the IMTPl, IMTPf at 1000 Hz and IMTPf. Post-hoc analysis with a Bonferroni adjustment was undertaken to identify the location of any differences. The ICC and CV, in addition to their associated CI were calculated using a custom designed spread sheet (13), all remaining data was analysed using the Statistical Package for Social Sciences (version 22, IBM, New York, USA). Data are presented as mean ± the standard deviation (SD), whilst statistical significance was set at $p \leq 0.05$.

RESULTS

Peak force

The IMTPl was highly reliable (CV = 3.10, 90% CI: 2.4 - 4.6%; ICC = 0.96, 90% CI: 0.90 - 0.98), and demonstrated a very strong correlation ($r = 0.96$, 90% CI: 0.90-0.98, p= < 0.0001) with no mean difference between sessions ($p = 0.49$) (Table 1). Furthermore, PF during the IMTPl was highly correlated ($r = 0.87$, $p < 0.0001$) and demonstrated acceptable validity (CV = 9.2, 90% CI: 7 - 14%; ICC = 0.88, 90% CI: 0.71-0.95) compared to IMTPf. A significant difference in mean PF existed between conditions ($p < 0.0001$), with the IMTPl demonstrating a systematic bias of -229.1 ± 154.5 N compared with the IMTPf (Table 1).

Place Table 1 Here

ACCEPTED

Copyright © Lippincott Williams & Wilkins. All rights reserved.

Time point specific force and rate of force development measures

Time specific force and accompanying RFD values, in addition to pRFD did not reach acceptable levels of validity or reliability for the IMTPl (Table 2 and 3). This was represented by a CV ranging from 16.2% (CI: 12.3-24.6%) to 73.4% (CI: 52.7-123.2) and ICC spanning -0.31 (-0.65 to 0.14) to 0.1 (-0.34 to 0.51). Correlations between conditions for these measures ranged from low (r = 0.15, 90% CI: -0.31 to 0.56) to high (r = 0.77, 90% CI: 0.50 to 0.90). The IMTPf reported stronger reliability for all measures taken at predetermined time points, in addition to pRFD, than the IMTPl (Figure 3).

Place Table 2 and 3 about here

Place Figure 3 about here

Down-sampling

A high level of validity resulted when PF was down-sampled from 1000 Hz to 100 Hz (CV = 0% CI: 0.0 - 0.1%; ICC = 1.0, CI = 1.0-1.0) (Figure4). Additionally, no difference (p = 0.37) and a practically perfect correlation (r = 1.0, p<0.0001) were noted for PF between the two sampling conditions (Figure 5). All remaining force-time measures also retained validity to the original frequency however significant differences ($p \leq 0.05$) were present in RFD measures at 30 and 50ms (Figure 5).

Place Figure 4 about here

Place Figure 5 about here

ACCEPTED

Copyright © Lippincott Williams & Wilkins. All rights reserved.

DISCUSSION

This study investigated the test-retest reliability and criterion validity of measures derived from a portable IMTP fitted with a single load-cell, in relation to a lab based version of the test. These findings support the primary hypothesis, which contended that PF for the IMTPl would reach acceptable levels of validity and reliability. This was represented by a high absolute and relative reliability as described by a CV of 3.1% and an ICC of 0.96, respectively. When determining reliability, the related CI can provide additional insight into the consistency of the measures in question. The results indicate the upper limit of the CI for the CV at 4.6%, and the lower CI limit for the ICC at 0.90, which are well within the 10% and 0.80 limits set for this study. As such, PF retains high levels of relative and absolute reliability between testing sessions, and gives further support to the consistency of this measure from the IMTPl. The smallest worthwhile change for this group (SD of day 2 × 0.2) of 53.41 N is greater than the error of the test (51.37 N). Therefore the IMTPl has the ability to detect even a small magnitude of effect (15). In addition to this, an acceptable level of validity was reached by the experimental condition (CV= 9.2%; ICC = 0.88). However, an examination of the CI associated with this measure indicates that the IMTPl falls outside of acceptable thresholds for both the upper limit of the CV (14%) and lower bound of the ICC (0.71). This suggests that the validity of this variable must be interpreted cautiously. Additionally, the IMTPl significantly underreported PF compared with IMTPf, represented by a systematic bias of -229.05 N. Taken together, this suggests that although very strongly related, the data generated from these two tests should not be compared.

A possible explanation for this bias is the more open-chain design of the IMTPl, which can impact force production in a number of ways. During the IMTPl, there is potential for anterior-posterior and medio-lateral movement of the bar in space. Considering that force

ACCEPTED

Copyright © Lippincott Williams & Wilkins. All rights reserved.

has both a magnitude and a direction in which it is applied, there is an increased likelihood of force being directed outside of the vertical axis. As IMTP assessments collect force-time data in the vertical axis only, lower values may well be obtained. A second, interrelated explanation considers that closed chain tasks provide greater proprioception (18, 20). Therefore, enhanced proprioception could translate into increased force in the intended direction of application. The decreased proprioception experienced by the performer in the IMTPl condition may limit the ability to locate the true vertical direction, therefore impairing the application of force in the measured axis. In pilot testing of this device, the authors employed a variety different cues to minimize misdirected force. This included “pull directly up”, and “do not lean back”. However, the pre-established instructions of applying small amount of pretension, followed by pulling as hard and as fast as possible was found most effective, and is recommended to practitioners. Neural factors may also contribute to the differences seen in this value. Specifically, isometric actions performed with identical joint configurations have reported different neural activation strategies between open and closed chain conditions, represented by a more simultaneous onset of activity for the musculature involved in the closed-chain task (27). Such a recruitment strategy would result in greater PF and RFD values than a more asynchronous activation (4). Accordingly, it is well documented that training interventions utilizing closed chain activities are superior for developing strength and RFD influenced capabilities when compared to open chain alternatives.(2)

The reliability of IMTPf RFD and time specific force measures were generally within, or slightly outside of acceptable reliability based on thresholds used previously for identical force-time curve analysis and methodology (ICC ≥ 0.7; CV $\leq 15\%$) (10). Peak RFD was measured from a 20ms sampling window, which has been reported to be the most reliable method for calculating pRFD (10). Rate of force development values at time points located

ACCEPTED

Copyright © Lippincott Williams & Wilkins. All rights reserved.

earlier in the force-time curve (30 and 50ms) were found less reliable and outside of these acceptable limits. This is in contrast to previous findings of acceptable reliability for corresponding measures amongst division I athletes extensively familiarized with this test (9). One possible explanation for discrepancies between the present study and previously published data may be explained by the lower training status and limited familiarization opportunities of the participants in this current investigation. Additionally, studies that have reported acceptable reliability have utilised a custom isometric testing system, which includes a bar made from cold-formed steel (3, 8, 10, 11, 19, 22, 30). In comparison, the criterion method in this present study utilized a traditional Olympic bar, which is less rigid than that of the custom system, and therefore may have impacted the characteristics of rate dependent variables. Despite these factors, the current data indicate that measures at predetermined time points and pRFD recorded by the IMTPl were not valid and found to be considerably less reliable than the IMTPf, while falling outside of the acceptable limits set by this or the aforementioned study.

The lack of validity and reliability in these measures may be underpinned by the same factors influencing systematically lower PF values. Specifically, the greater potential for unintended shifts in the direction of the applied force during the pull in the experimental condition could conceivably impact time specific measures. Small deviations from the vertical axis in this limited time frame (< 250ms) may well be responsible in large part for the inconsistencies in these measures. Additionally, it is possible that the training status of the participants contributed to the observed results. In particular, this present study used recreationally active males with only ≥ 6 months of structured resistance training experience. As a vector quantity, a resultant force produced by the neuromuscular system is intimately linked with the ability to apply that force in the intended direction of measure. Thus, a more

ACCEPTED

Copyright © Lippincott Williams & Wilkins. All rights reserved.

trained population with a greater force capacity would possess an increased level of innate proprioception allowing the more consistent application of force in a chosen direction. This may result in improved validity and reliability for force-time measures. However, it is plausible that the greater reliability expected for stronger populations may still not reach an acceptable level. Accordingly, our findings support the statement that similar, more-open chain portable designs of IMTPf are acceptable for PF only within athletic populations (7). Taken together this indicates that it is largely the design of the apparatus rather than the instrumentation itself (load-cell or force plate) that impacts its reliability. However, the construction of the system and the instrumentation are related, whereby the use of a single load-cell limits the potential configuration of an IMTP.

Down-sampling of force plate data was undertaken to ensure that any differences between measures were calculated independent of sampling frequency. The primary finding in the context of this article is that PF at 100 Hz retained validity in relation to the higher sampling frequency. Specifically, near perfect correlations (r = 1.0, p<0.0001) were found, in addition to excellent validity (CV = 0% CI: 0.0 - 0.1%; ICC = 1.0, CI = 1.0 - 1.0), with no differences noted between these two sampling rates (p= 0.37; 90%CI= -0.6 to 0.6). Thus, comparisons of PF between the criterion and experimental condition were unaffected when 1000 Hz data was reduced to 100 Hz. Although down-sampled RFD and time specific force measures all achieved validity to the original frequency, significant differences were present at earlier RFD time points. Specifically, lower RFD values at 30 and 50 ms were noted at 1000 Hz when compared to 100 Hz. Such differences can be explained by the loss of sensitivity in the down-sampled data when determining the onset point and corresponding force value, from which time specific measures are taken. This shifts the second time point of the measure to a differing force sample and potentially a changed value also. These findings

ACCEPTED

Copyright © Lippincott Williams & Wilkins. All rights reserved.

are similar to previous findings which showed notable differences when GRF data was down-sampled to 100 Hz from 500 Hz (16).

The primary purpose of this present study was to determine if an IMTPf could be reproduced with a single-axial load cell and easily accessible materials to accurately measure PF. These findings confirm that an IMTPl is a valid and highly reliable method for assessing maximal isometric force in a similar fashion to the IMTPf. The very high correlation between the two conditions indicates a strong relationship is present for the measure of PF. However, the validity of the experimental method in relation to the criterion test must be interpreted cautiously, as a significant negative systematic bias is present. Secondary to this, time-point specific measures and pRFD failed to reach acceptable thresholds of reliability and validity for the experimental method.

PRACTICAL APPLICATIONS

The IMTPl is suitable for a variety of purposes in strength and conditioning, sports science, and rehabilitation fields. Specifically, measuring PF via this test has sufficient relative reliability to assess the relevance of maximal strength to a given athlete population or sport. A high absolute reliability further broadens the use of this instrument. In particular, the IMTPl has suitable application as a monitoring tool, allowing for the reliable assessment and comparison of changes in performance. This apparatus would be appropriate to provide an objective determination on factors such as: a) the effectiveness of training interventions; b) the magnitude of detraining; c) the impact of fatigue; d) the preparedness for competition; and e) the return to function from injury (17, 24). However, it is important for coaches and researchers to recognize that the IMTPl is a slightly different test to the criterion condition, with athletes likely to produce a significantly greater result in the IMTPf. With this in mind

ACCEPTED

Copyright © Lippincott Williams & Wilkins. All rights reserved.

the authors advise against comparing the results between devices or using them interchangeably. Regardless, if an athlete produces good results in one of these conditions, they can be expected to perform well in the other. Additionally, the particular advantage of the IMTPl over the IMTPf is its affordability and portability. This allows the device to be used in a variety of areas in strength and conditioning settings, including with developmental athletes and in higher performance clubs, while more easily traveling with teams for competition or training camps (12). Furthermore, these results were attained with only a within session familiarization protocol. This suggests that minimal learning is required, allowing for valuable data to be collected easily and in a time efficient manner. This makes the IMTPl an acceptable alternative to the IMTPf for practitioners who wish to measure and monitor maximal strength.

ACCEPTED

Copyright © Lippincott Williams & Wilkins. All rights reserved.

REFERENCES

1. Atkinson G and Nevill AM. Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. *Sports Med* 26: 217-238, 1998.
2. Augustsson J, Esko A, Thomeé R, and Svantesson U. Weight training of the thigh muscles using closed versus open kinetic chain exercises: a comparison of performance enhancement. *J Orthop Sports Phys Ther* 27: 3-8, 1998.
3. Beckham G, Mizuguchi S, Carter C, Sato K, Ramsey M, Lamont H, Hornsby G, Haff G, and Stone M. Relationships of isometric mid-thigh pull variables to weightlifting performance. *The Journal of sports medicine and physical fitness* 53: 573-581, 2013.
4. Cormie P, McGuigan M, and Newton R. Developing maximal neuromuscular power: part 1. *Sports Med* 41: 17-38, 2011.
5. Cormie P, McGuigan M, and Newton R. Developing maximal neuromuscular power: part 2--Training considerations for improving maximal power production. *Sports Med* 41: 125-146, 2011.
6. Currell K and Jeukendrup AE. Validity, reliability and sensitivity of measures of sporting performance. *Sports Med* 38: 297-316, 2008.
7. Haff GG. The mid-thigh pull: A method of evaluating athlete preparedness. *J Aust Strength Cond* 21: 8, 2013.
8. Haff GG, Carlock JM, Hartman MJ, Kilgore JL, and et al. Force-time curve characteristics of dynamic and isometric muscle actions of elite women Olympic weightlifters. *J Strength Cond Res* 19: 741-748, 2005.
9. Haff GG and Nimphius S. Training principles for power. *Strength Cond J* 34: 2-12, 2012.
10. Haff GG, Ruben RP, Lider J, Twine C, and Cormie P. A comparison of methods for determining the rate of force development during isometric midthigh clean pulls. *J Strength Cond Res* 29: 386-395, 2015.
11. Haff GG, Stone M, O'Bryant HS, Harman E, Dinan C, Johnson R, and Han K-H. Force-time dependent characteristics of dynamic and isometric muscle actions. *J Strength Cond Res* 11: 269-272, 1997.
12. Harris NK, Cronin J, Taylor K-L, Boris J, and Sheppard J. Understanding position transducer technology for strength and conditioning practitioners. *Strength Cond J* 32: 66-79, 2010.
13. Hopkins W. Reliability from construct pairs of trials (Excel spreedsheet) *A New View of Statistics Internet Society for Sport Science,* 2000, Available at: http://www.sportsci.org/resources/stats/xrely.xls.
14. Hopkins WG. Measures of reliability in sports medicine and science. *Sports Med* 30: 1-15, 2000.
15. Hopkins WG. How to interpret changes in an athletic performance test. *Sportscience* 8: 1-7, 2004.
16. Hori N, Newton RU, Kawamori N, McGuigan MR, Kraemer WJ, and Nosaka K. Reliability of performance measurements derived from ground reaction force data during countermovement jump and the influence of sampling frequency. *J Strength Cond Res* 23: 874-882, 2009.
17. Impellizzeri F, Rampinini E, and Marcora S. Physiological assessment of aerobic training in soccer. *J Sports Sci* 23: 583-592, 2005.
18. Kavounoudias A, Roll R, and Roll J-P. The plantar sole is a ‘dynamometric map’for human balance control. *Neuroreport* 9: 3247-3252, 1998.

ACCEPTED

Copyright © Lippincott Williams & Wilkins. All rights reserved.

19. Kawamori N, Rossi SJ, Justice BD, Haff EE, Pistilli EE, O'Bryant HS, Stone MH, and Haff GG. Peak force and rate of force development during isometric and dynamic mid-thigh clean pulls performed at various intensities. *J Strength Cond Res* 20: 483-491, 2006.

20. Kiefer G, Forwell L, Kramer J, and Birmingham T. Comparison of sitting and standing protocols for testing knee proprioception. *Physiotherapy Canada* 50: 30-34, 1998.

21. Knudson D. Significant and meaningful effects in sports biomechanics research. *Sports Biomech* 8: 96-104, 2009.

22. Kraska JM, Ramsey MW, Haff GG, Fethke N, Sands WA, Stone ME, and Stone MH. Relationship between strength characteristics and unweighted and weighted vertical jump height. *Int J Sports Physiol Perform* 4: 461-473, 2009.

23. Lauersen JB, Bertelsen DM, and Andersen LB. The effectiveness of exercise interventions to prevent sports injuries: a systematic review and meta-analysis of randomised controlled trials. *Br J Sports Med* 48: 871-877, 2014.

24. Muller E, Benko U, Raschner C, and Schwameder H. Specific fitness training and testing in competitive sports. *Med Sci Sports Exerc* 32: 216-220, 2000.

25. Nuzzo JL, McBride JM, Cormie P, and McCaulley GO. Relationship between countermovement jump performance and multijoint isometric and dynamic tests of strength. *J Strength Cond Res* 22: 699-707, 2008.

26. Paavolainen L, Häkkinen K, Hämäläinen I, Nummela A, and Rusko H. Explosive-strength training improves 5-km running time by improving running economy and muscle power. *J Appl Physiol* 86: 1527-1533, 1999.

27. Stensdotter A-K, Hodges PW, Mellor R, Sundelin G, and Hager-Ross C. Quadriceps activation in closed and in open kinetic chain exercise. *Med Sci Sports Exerc* 35: 2043-2047, 2003.

28. Stone MH, Moir G, Glaister M, and Sanders R. How much strength is necessary? *Phys Ther Sport* 3: 88-96, 2002.

29. Stone MH, O Bryant HS, McCoy L, Coglianese R, Lehmkuhl M, and Schilling B. Power and maximum strength relationships during performance of dynamic and static weighted jumps. *J Strength Cond Res* 17: 140-147, 2003.

30. Stone MH, Sanborn K, O Bryant HS, Hartman M, Stone ME, Proulx C, Ward B, and Hruby J. Maximum stength-power-performance relationships in collegiate throwers. *J Strength Cond Res* 17: 739-745, 2003.

31. Thomas C, Comfort P, Chiang C-Y, and A. Jones P. Relationship between isometric mid-thigh pull variables and sprint and change of direction performance in collegiate athletes. *Journal of Trainology* 4: 6-10, 2015.

ACCEPTED

Copyright © Lippincott Williams & Wilkins. All rights reserved.

Figure legends

Figure 1. Testing conditions. Criterion isometric mid-thigh clean pull condition (IMTPf) (A) and experimental isometric mid-thigh clean pull condition (IMTPl) (B).

Figure 2. Design of the criterion condition base plate. Transverse view above (A), frontal view (B) and transverse view from below (C).

Figure 3. Reliability of the criterion condition. Mean ± 90 % confidence interval for the intraclass correlation (A) and coefficient of variation (B) of the rate of force development, and mean ± 90 % confidence interval for the intraclass correlation (C) and coefficient of variation (D) of force at time points.

Figure 4. Validity of the criterion condition at 100 Hz when compared to the original 1000 Hz frequency. Mean ± 90 % confidence interval for the intraclass correlation (A) and coefficient of variation (B) of the rate of force development, and mean ± 90 % confidence interval for the intraclass correlation (C) and coefficient of variation (D) of force at time points.

Figure 5. Values for each measure in each condition. Mean ± SD for rates of force development (A) and force at time points (B) in the isometric mid-thigh clean pull with a force plate (IMTPf) sampling at 1000 Hz, IMTPf sampling at 100 Hz and isometric mid-thigh clean pull with a load cell (IMTPl) sampling at 100 Hz. PF, peak force; pRFD, peak rate of force development. # $p < 0.05$ difference between IMTPf 1000 Hz and IMTPl 100 Hz, † $p < 0.05$ difference between IMTPf 100 Hz and IMTPl 100 Hz, ‡ $p <$ difference between IMTPf 1000 Hz and IMTPf 100 Hz.

ACCEPTED

Copyright © Lippincott Williams & Wilkins. All rights reserved.

Reliability	
Day 1 (mean ± SD)	1592.85 ± 232.03 N
Day 2 (mean ± SD)	1657.14 ± 267.04 N
ICC (90%CI)	0.96 (0.90 - 0.98)
CV (90%CI)	3.1 % (2.4 - 4.6 %)
r **=**	0.96
p **=**	0.49
Validity	
IMTPf (mean ± SD)	1854.04 ± 315.64 N
IMTPl (mean ± SD)	1625.00 ± 246.92 N
ICC (90%CI)	0.88 (0.71 - 0.95)
CV (90%CI)	9.2 % (7 – 14 %)
Systematic bias	–229.05 N
r **=**	0.87
p **=**	<0.0001

Table 1. Test-retest reliability for the measure of peak force in the experimental condition, and criterion validity between the experimental (IMTPl) and criterion conditions (IMTPf). ICC: Intraclass correlation coefficient; CV: Coefficient of variation; CI: Confidence intervals.

ACCEPTED

Copyright © Lippincott Williams & Wilkins. All rights reserved.

	Validity						
	0-30ms	**0-50ms**	**0-100ms**	**0-150ms**	**0-200ms**	**0-250ms**	**Peak RFD**
ICC	-0.160	0.140	0.210	0.390	0.520	0.660	0.320
ICC 90% CI	(-0.28-0.55)	(-0.3-0.54)	(-0.24-0.58)	(-0.05-0.7)	0.13-0.78	0.33-0.85	(-0.12-0.66)
CV (%)	42.2	42.2	31.6	18.7	11.7	8.8	20.9
CV 90% CI (%)	32.5-70.6	31.1-67.1	23.5-49.3	14.1-28.5	8.9-17.6	6.7-13.1	15.7-32.0
r	0.163	0.145	0.203	0.388	0.537	0.669	0.30
	Reliability						
	0-30ms	**0-50ms**	**0-100ms**	**0-150ms**	**0-200ms**	**0-250ms**	**Peak RFD**
ICC	-0.260	-0.280	-0.310	-0.280	-0.12	0.1	-0.19
ICC 90% CI	(-0.62-0.18)	(-0.63-0.16)	(-0.65-0.14)	(-0.63-0.17)	(-0.52-0.33)	(-0.34-0.51)	(-0.57-0.26)
CV (%)	73.4	69.5	51.6	32.3	20.8	17.3	40.3
CV 90% CI (%)	52.7-123.2	50.0-116.0	37.7-83.5	24.0-50.5	15.6-31.8	13.1-26.3	29.7-63.9
r	-0.262	-0.281	-0.308	-0.310	-0.129	0.107	-0.195

Table 2: Criterion validity for rate of force development measures, and test-retest reliability for these measures in the experimental condition. ICC: Intraclass correlation coefficient; CV: Coefficient of variation; CI: Confidence intervals.

ACCEPTED

Copyright © Lippincott Williams & Wilkins. All rights reserved.

	Validity					
	30ms	**50ms**	**100ms**	**150ms**	**200ms**	**250ms**
ICC	0.160	0.140	0.210	0.390	0.52	0.66
ICC 90% CI	(-0.28-0.55)	(-0.3-.54)	(-0.24-0.58)	(-0.05-0.7)	0.13-0.78	0.33-0.85
CV (%)	39.5	39.7	31.1	18.7	11.6	8.7
CV 90% CI (%)	29.2-62.2	29.3-62.9	23.2-48.6	14.1-28.4	8.8-17.4	6.6-12.9
r	0.163	0.145	0.203	0.388	0.537	0.669
	Reliability					
	30ms	**50ms**	**100ms**	**150ms**	**200ms**	**250ms**
ICC	-0.26	-0.28	-0.31	-0.28	-0.12	0.1
ICC 90% CI	(-0.62-0.18)	(-0.63-0.16)	(-0.65-0.14)	(-0.63-0.17)	(-0.52-0.33)	(-0.34-0.51)
CV (%)	40	50.2	45.7	29.9	19.4	16.2
CV 90% CI (%)	29.5-63.5	36.7-81.1	33.6-73.3	22.3-46.5	14.6-29.6	12.3-24.6
r	-0.262	-0.281	-0.308	-0.310	-0.129	0.107

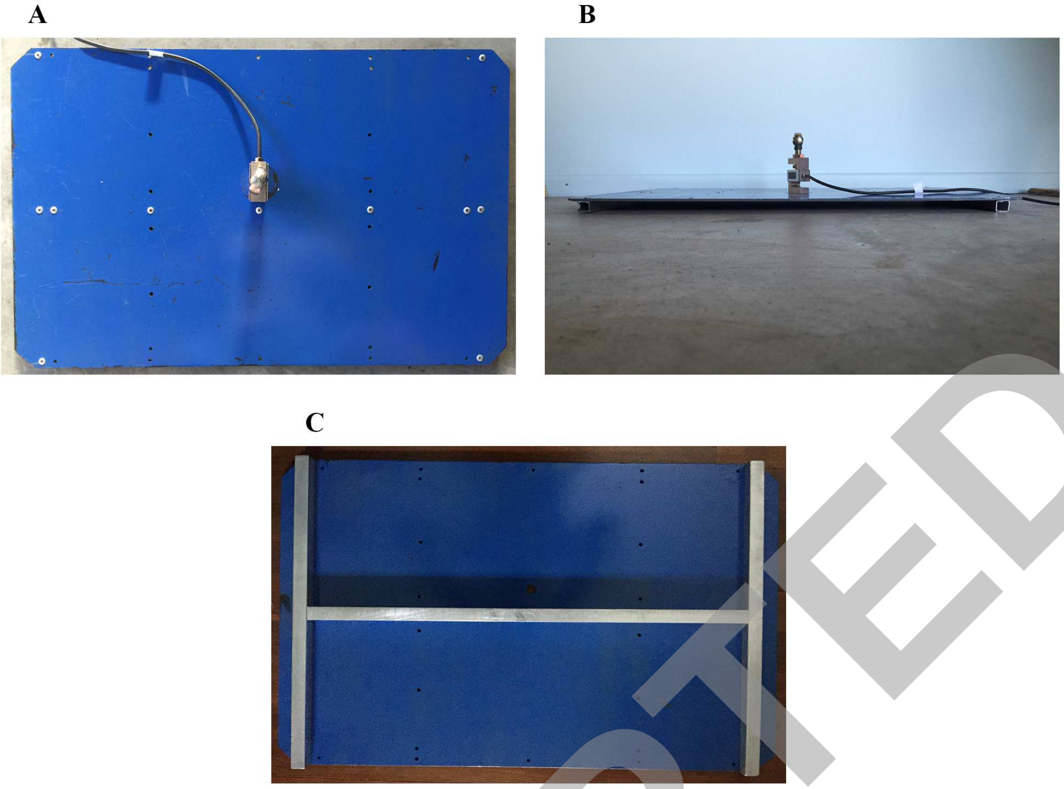
Table 3: Criterion validity for force at selected time point measures, and test-retest reliability for these measures in the experimental condition. ICC: Intraclass correlation coefficient; CV: Coefficient of variation; CI: Confidence intervals.

ACCEPTED

Copyright © Lippincott Williams & Wilkins. All rights reserved.

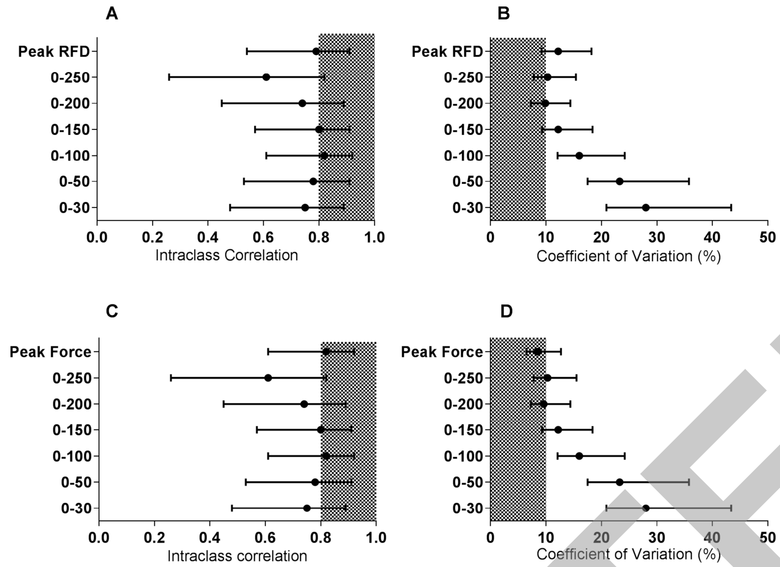
ACCEPTED

Copyright © Lippincott Williams & Wilkins. All rights reserved.



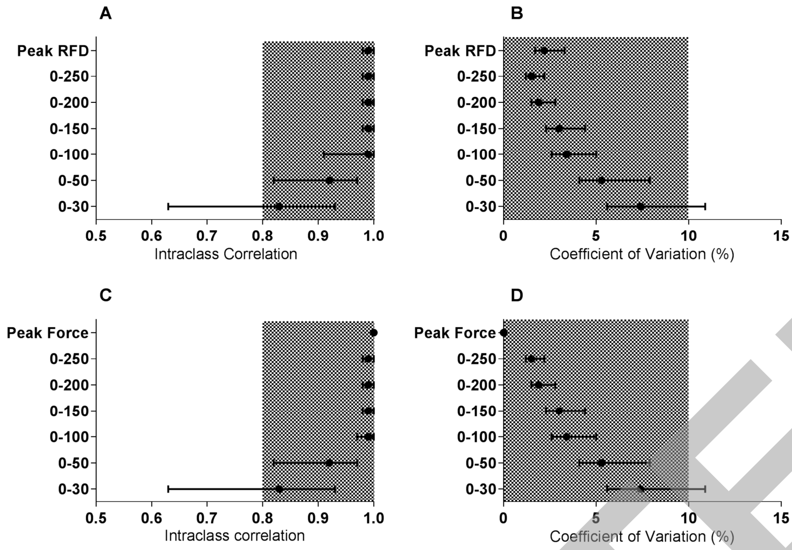
ACCEPTED

Copyright © Lippincott Williams & Wilkins. All rights reserved.



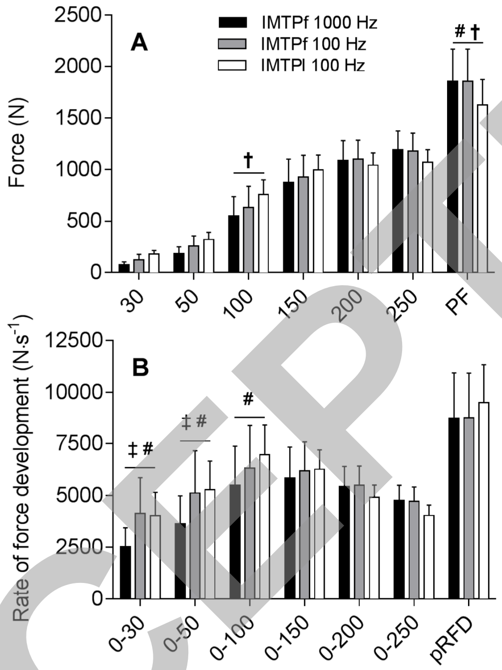
ACCEPTED

Copyright © Lippincott Williams & Wilkins. All rights reserved.



ACCEPTED

Copyright © Lippincott Williams & Wilkins. All rights reserved.



ACCEPTED

Copyright © Lippincott Williams & Wilkins. All rights reserved.